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Preliminary Investigation into the Development of Hardening Devices Using Vacuum Microelectronics Technology

by Chance M. Glenn

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13. ABSTRACT (Maximum 200 words) Recently there has been a resurgence of interest in the vacuum valve. Manufacturing capabilities in the area of semiconductor microelectronic devices have paved the way for the emergence of vacuum microelectronic ($V\mu E$) technology. The possibility of these new devices becoming a robust, high-speed alternative to solid-state electronics has caught the interest of the system hardening community. The most fundamental question asked is whether or not these field emission devices can be incorporated into electronic systems as limiters—the most basic hardening device for in-band front-door hardening. This investigation shows that not only is it possible for these devices to be developed into an alternative to conventional semiconductor limiters, but there may also be marked operational advantages.				
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1. Introduction

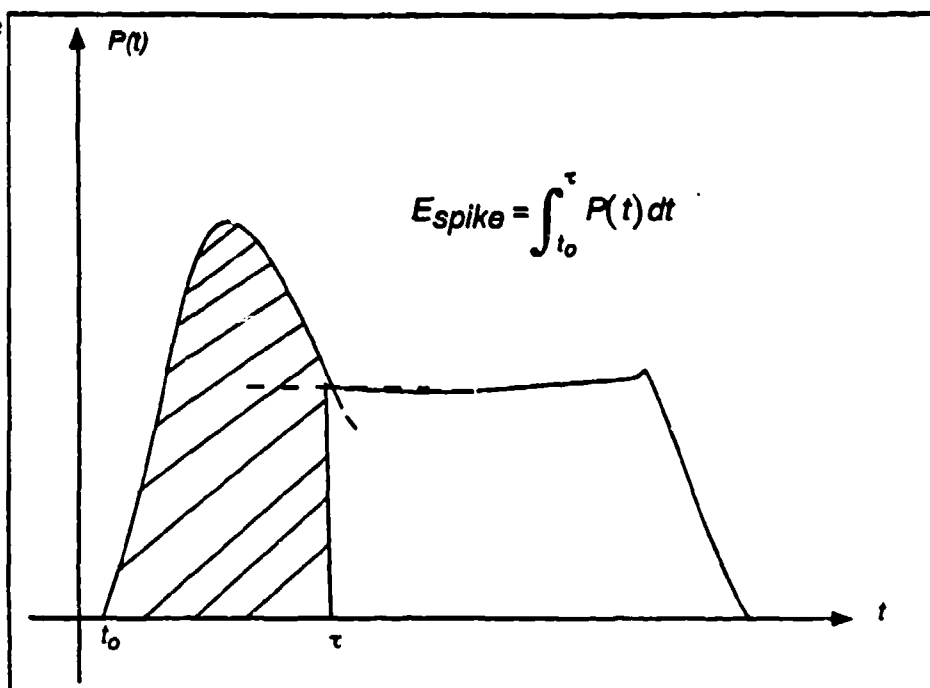
The importance of this investigation hinges on the question of whether or not $V_{\mu}E$ technology can be exploited to design a better limiting device. Most limiter designs are nothing more than a conditional short circuit to ground. As they stand, conventional limiters are semiconductor p-n junction devices. There is much concern over the speed and robustness of conventional limiters in ever-increasing hostile environments.

The speed of a semiconductor device such as a metal semiconductor field effect transistor (MESFET) is ultimately limited by the time it takes for an electron to travel from the source to the drain. Impurity and phonon collisions within the lattice of the solid lead to electron velocity saturation at near the speed of sound [1]. Vacuum valves operate by electrons passing from cathode to anode uninterrupted by molecular collisions. This is called ballistic transport. Typical voltages (100 V) and dimensions (1 μm) yield transit times less than 1 ps [2]. Complete switching times are impaired by parasitic capacitances, which are characteristic of small devices, as well as packaging capacitance. Still, $V_{\mu}E$ provides the technology for extremely fast switching and, ultimately, extremely fast limiting.

Most semiconductor devices rely on low-voltage transport in a low-density electron gas. Ionizing radiation can cause an excitation of carriers, changing the density of the electron gas, thus leading to significant shifts in bias voltage. The result may be transient upset, or permanent damage, which is evident from previous experimentation [3]. Vacuum valves have greater immunity to such perturbations since the source of electrons is either a metal or highly doped silicon cathode. Vacuum valves also work at much higher voltages than semiconductors, again making them far less sensitive to large voltage pulses.

In any protection device that operates by short-circuiting delicate components, this very low impedance alternative path must be initiated before the transient pulse causes damage. Spike leakage is energy that "leaks" through before the device is completely turned on (see fig. 1). $V_{\mu}E$ technology provides the hope of reducing this energy while maintaining a sufficiently robust device.

Figure 1. Spike leakage of a typical PIN diode limiter.



2. Literature Search Results

The first step in this investigation was a literature search. The goal was to gain a basic knowledge of the technology as well as become aware of the latest developments in the field. This was necessary in order to make reasonable judgments as to whether this technology could lend itself to the development of hardening devices comparable to existing semiconductor models.

2.1 Technology Overview

The emission of electrons from the cathode, modulation of the electron beam by a grid, and collection at the anode is the basis of operation of most vacuum electronic devices. The energy required to strip an electron free from its parent nucleus is the work function, which is obviously different for different materials. Traditional vacuum tubes exploit the process of thermionic emission, where electrons are "boiled off" from the cathode by a heater. The electron stream is then modulated by a grid and collected at the anode. Microelectronic fabrication technology has provided the ability to create devices with this same fundamental operation, yet on a microscopic scale. With $V_{\mu E}$ devices, electron emission is induced by the high electric fields produced due to specific geometry. This is field emission.

Field emission provided one of the first successes of quantum mechanics when Fowler and Nordheim were able to explain it in terms of tunnelling through a triangular energy barrier [1] (see fig. 2). The Fowler-Nordheim equation, derived from this work in a basic form, describes the current density J in terms of the work function ϕ and the electric field E . It is, approximately,

$$J = \alpha E^2 \phi^{-1} \exp\left(\frac{-\beta \phi^{\frac{3}{2}}}{E}\right), \quad (1)$$

where α and β are constants. The experimental study of field emission then became very active in the 1930's with attempts to confirm the Fowler-Nordheim theory using experimental techniques. Since then, work has been done to further understand and refine this process in order to fabricate devices operating under field emission principles.

In field emission, it is the high electric field at the cathode surface which allows quantum-mechanical tunnelling through the approximately triangular energy barrier. Two particular field emitter geometries emerged: point-to-plane and plane-to-plane (see fig. 3). The high concentration of the electric field at very sharp tips makes point-to-plane geometry more ideal. Present technology can manufacture field emission tips whose radii of curvature are in angstroms. Plane-to-plane geometry requires well-defined, ultra-flat electrode surfaces. Electrical breakdown between flat electrical surfaces is not yet well enough understood to make predictions and exploit these predictions in the fabrication of a stable device. What is known is that microscopic, whisker-like protrusions on the plane are factors in initiating electrical breakdown.

Figure 2. Schematic energy diagram for field emission.

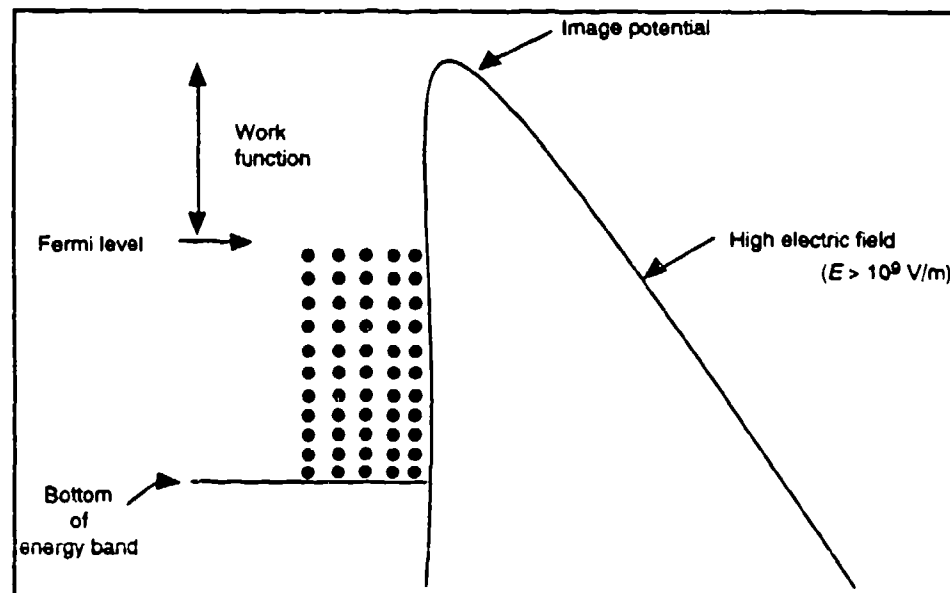
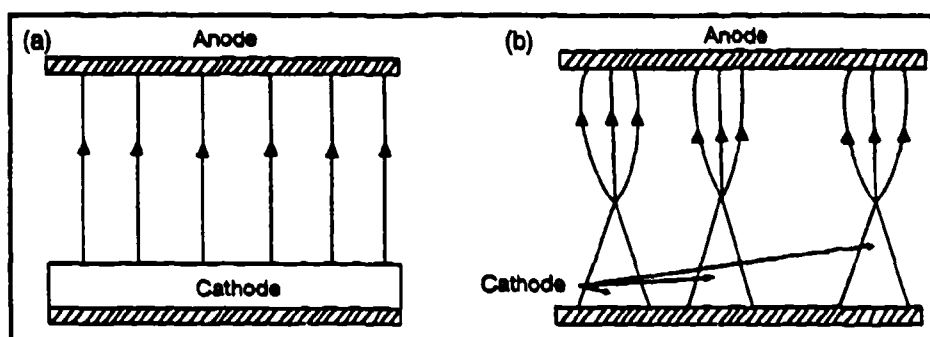


Figure 3. (a) Plane-to-plane and (b) point-to-plane field emitter geometries.



The merger of point-to-plane and plane-to-plane geometries led to the concept of field emitter arrays (FEA's). Several thousand field emitter tips are spaced closely together to form an FEA. One advantage of the FEA structure is that large arrays can be built, thus allowing high currents to flow. The maximum current density J_{max} (A/cm²) of the FEA is on the order of 4×10^4 and is independent of the applied voltage [4]. Using this maximum current density and a typical value of 100 μ A / tip, we can see that a typical FEA has about 4×10^8 tips/cm². These values are being pushed to higher and higher limits through continuous experimentation with new materials and the application of better fabrication techniques.

2.2 Fabrication

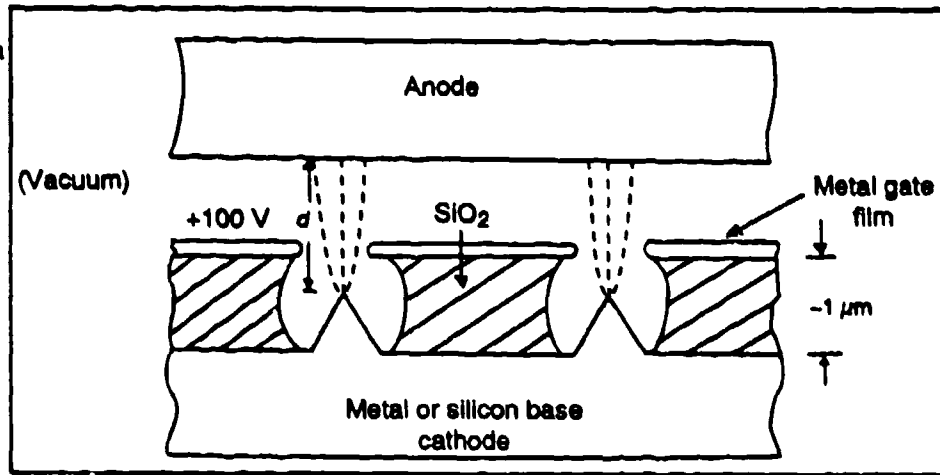
If we consider the distance (d) as the length between the cathode tip and the anode surface (see fig. 4), we must have some criteria to determine whether an electron travelling along that path is indeed travelling within a vacuum. When (d) is much smaller than the electron mean free path (λ_e) for collision with residual gas, we consider the medium a vacuum [5]. We define λ_e as

$$\lambda_e = \frac{T}{273 p P_c(V)} [\text{cm}] , \quad (2)$$

where $P_c(V)$ is the probability of collision, T is the absolute temperature in kelvins, and p is the pressure in torr. The practical limits on fabrication technology allow for $d = 0.5 \mu\text{m}$. Now, given that the probability of collision in a particular distance x is given by

$$p(x) = 1 - e^{-x/\lambda_e} \approx x/\lambda_e \text{ for } x/\lambda_e \ll 1 , \quad (3)$$

Figure 4. Schematic of a typical field emission gated diode.



then

$$d \leq 10^{-2} \lambda_e, \quad (4)$$

if we assume that the device can tolerate one in every one hundred electron collisions, or $p(x) = 1/100$. For this calculation we let the temperature $T = 300$ K and the pressure $p = 760$ torr.

Fabrication techniques developed from integrated circuit technology have been directly adapted to the fabrication of FEA's. Some of these techniques are as follows: anisotropic etching of metals and semiconductors, etching of a unidirectional solidified eutectic, and the use of deposition techniques, in conjunction with ultraviolet (UV) or electron beam lithography. Figure 5 is a progression diagram illustrating a UV lithography fabrication process developed by the Naval Research Laboratory, using silicon (Si) and silicon-dioxide (SiO_2) [1]. Figure 6 shows a chemically selective wet-etching technique developed by Science Applications International Corporation (SAIC), using a semiconductor-metal eutectic composite material Si-TaSi_2 . In both techniques there is an attempt to control the tip height while minimizing the tip radius.

Field emission is very sensitive to surface work function, electric field, and the field-enhancing tip shape. Although this is indeed true, cathodes have still shown very long lifetimes [1,6]. Surface cleanliness, atomic contamination, and lack of tip uniformity have been shown to play a large role in FEA performance over time.

Figure 5. Progression diagram of a UV lithographic fabrication technique.

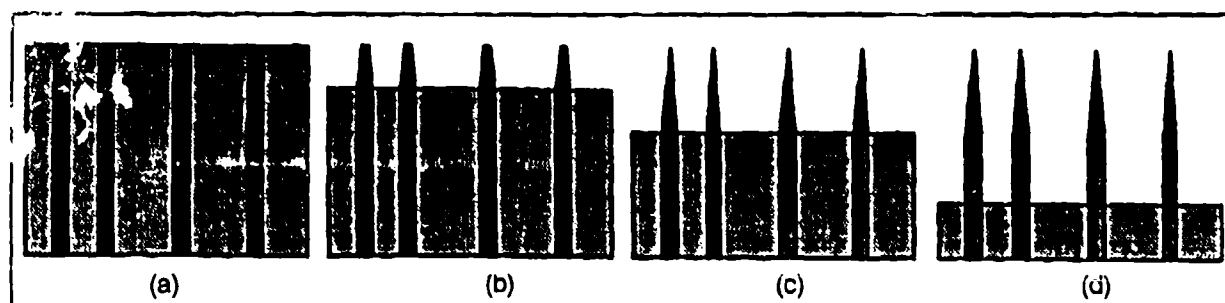
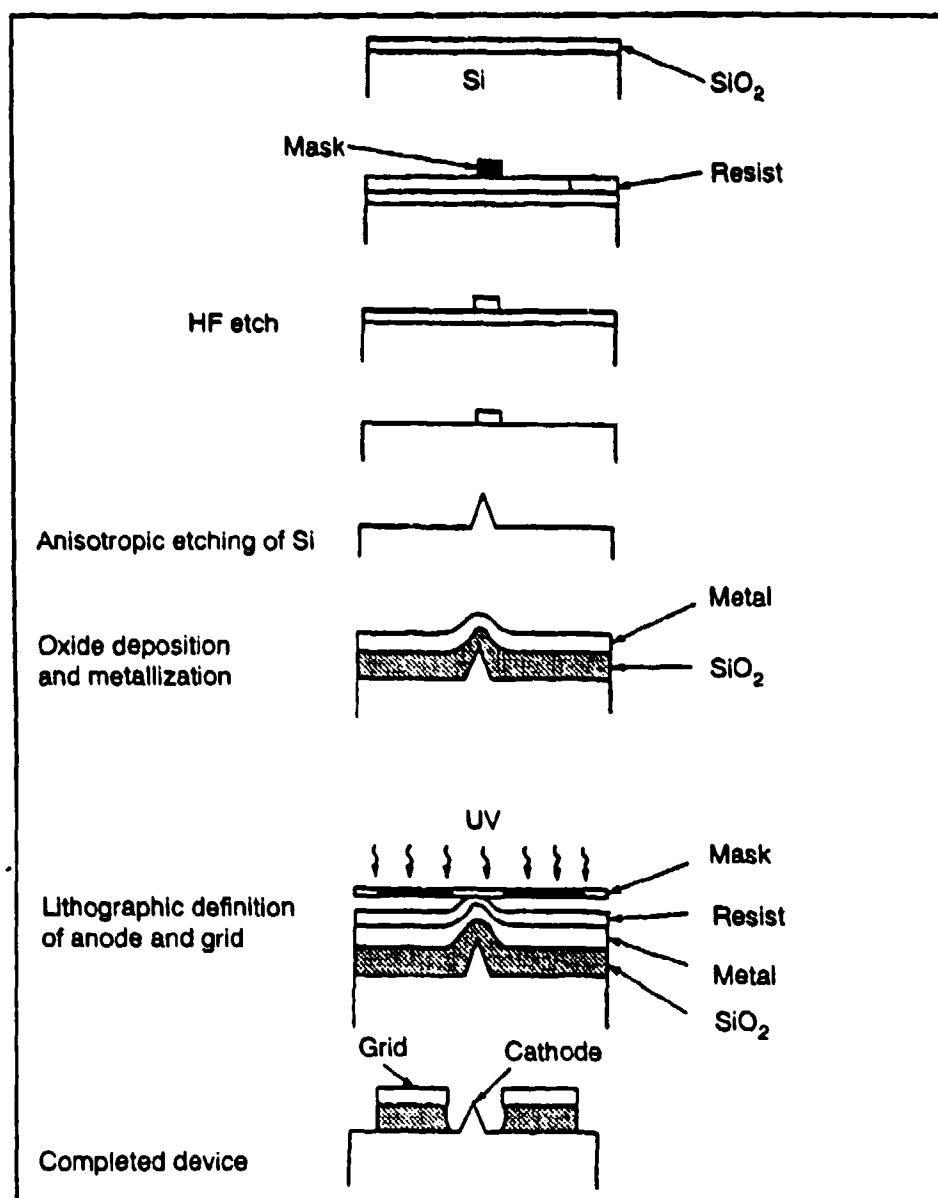


Figure 6. Progression diagram of a eutectic wet-etching fabrication technique.

3. Experimentation

At the present time, SAIC has development underway for several prototype vacuum diode limiters for the Army Research Laboratory (ARL). Their designs must be compatible for microwave circuitry. After the devices are designed and fabricated, they will undergo testing here at ARL, Adelphi. Later reports will present the results of this experimentation.

Contacts through the Naval Research Laboratory (NRL) have produced the possibility of another manufacturer. The Microelectronics Center of North Carolina (MCNC) at Research Triangle Park has been working with NRL for several years in their research and fabrication techniques [7,8]. It may be possible to tap into the resources they have developed in order to obtain workable devices for microwave research.

4. Hardening Device Configurations

The primary hardening device under consideration is the limiter. Conventional limiters operate by providing a conditional short to ground. The conditions are determined by the switching device (i.e., PIN diode). As stated earlier, we are convinced that $V_{\mu E}$ devices have the potential to present advantages over PIN diodes in turn-on speed and power handling capability. If this is the case, then limiter circuits can be designed that do not allow as much spike leakage as PIN diodes with thin I-regions, and can handle more power than PIN diodes with thick I-regions. More power handling capability compared to PIN diodes is desirable since the $V_{\mu E}$ device can then handle electromagnetic pulse (EMP) signals. Limiter designs come in two classes at the present time: the first is the conditional short to ground and the second is the limiting attenuator.

4.1 Conditional Short to Ground

Figure 7 shows a typical two-element limiter. Here $V_{\mu E}$ devices are substituted for PIN diodes. One of the immediate disadvantages of this device can be visualized from the I-V characteristics of a typical Si FEA, shown in figure 8. The turn-on voltage of the device is about 120 to 130 V compared to 0.7 V for Si PIN diodes. When the goal is to protect the front door of communications systems, the power needed to turn on the limiter may be well above the system's threshold. However, research is ongoing to try to bring down the turn-on voltage.

Figure 7. Possible configuration for a dual $V_{\mu E}$ element limiter.

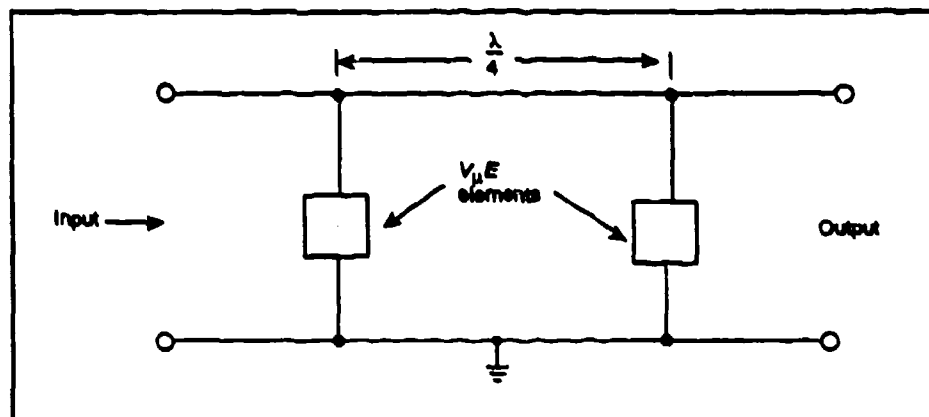
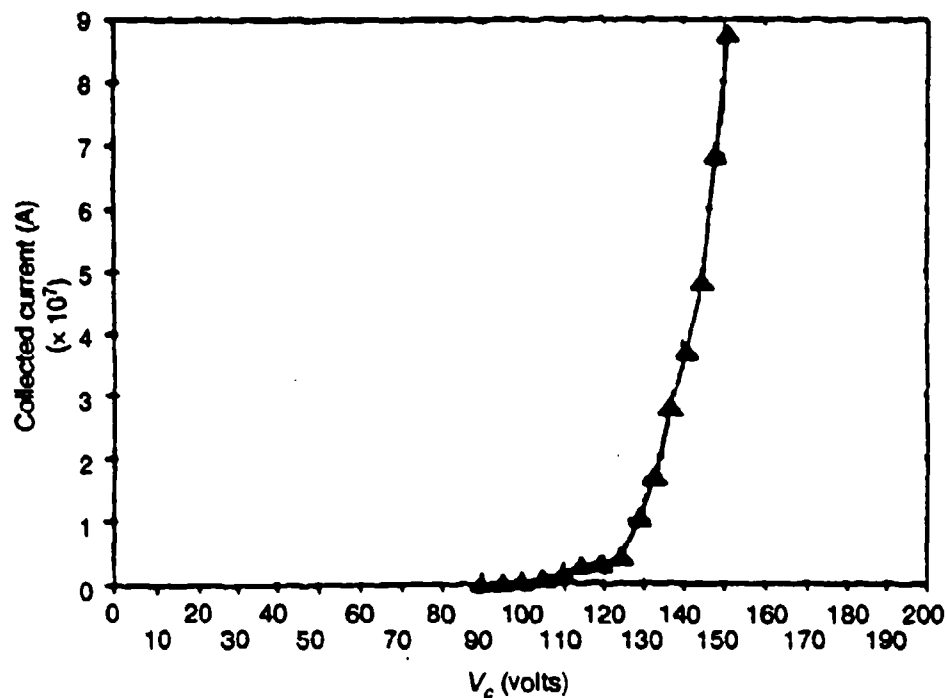


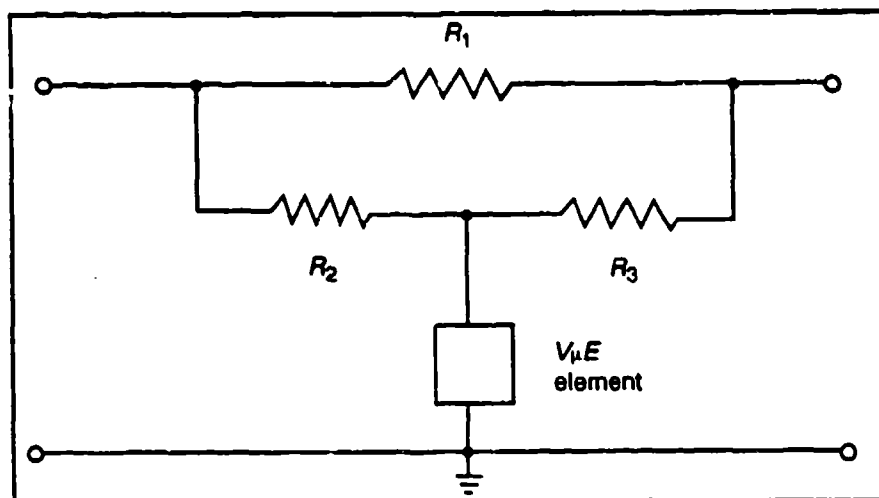
Figure 8. I-V characteristics of a typical Si FEA.



4.2 Limiting Attenuator

Another limiter configuration is a design that provides limiting by absorption. The goal is to reduce the reflected power. This may be advantageous for military systems. Figure 9 is an example of a possible limiting attenuator. The nonlinear property of the $V_{\mu E}$ device switches in a π -network attenuator when the input power exceeds a threshold. Another advantage of a circuit similar to this is that it may be possible to design in the threshold level. Work is continuing at ARL to develop better circuit designs for this type of limiter [9]. It may be possible to incorporate a $V_{\mu E}$ device into the design.

Figure 9. Possible configuration for a limiting attenuator circuit using a $V_{\mu}E$ element.



5. Future Work

Several things are yet to be done to complete this work. First of all, efforts must continue to gain further knowledge of the $V_{\mu}E$ technology, as well as staying abreast of the latest developments in the field. This will be a result of continued literature search and study as well as observation and experimentation. The fact that this is a relatively new field means that progress will be made quickly from level to level. It is our hope to successfully apply this technology to hardening devices, which calls for a deeper understanding of the entire design/fabrication process. Secondly, we must be able to develop a microwave limiter design into a tangible realistic circuit. Although the basic technology alludes to a feasible device, we must find out whether packaging restrictions will deny us the advantages we seek. Thirdly, complete microwave characterizations of manufactured devices must be made if indeed we are able to overcome some of the design barriers. Not only will we attempt to verify other experimentation being done at other facilities, but we will also attempt to generate new characterizations of $V_{\mu}E$ devices in the microwave arena. Finally, we will attempt to bring ARL into the network of research and information regarding this technology.

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